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FREE ELECTRON LASERS AND
MAGNETIC MATERIALS (*)

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ABSTRACT

Free Electron Lasers (FELs), offering coherent, tunable, high power submillimeter radiation, open exciting areas of magnetic materials research. At the same time, FELs have benefited from magnetic materials research - specifically the modern development of Rare Earth Cobalt and Neodymium-Iron-Boron permanent magnet materials. Application of these materials to a new type of short period FEL undulator is described.

INTRODUCTION

Free Electron Lasers (FELs) are of interest to the magnetics community both as a research tool and as an interesting application of permanent magnet materials. One such application will be the subject of this paper.

As a research tool of particular interest to the magnetics community, the FEL's unique high power and tunability throughout the submillimeter and far infrared wavelengths are usefull, for example, for spectroscopy of magnetic resonances, generation of spin waves in large band-gap ferro-magnetic systems, and the study of non-linear magnon modes.

On the other hand, the development of FELs has benefited enormously from the development of modern magnetic materials - specifically Rare Earth Cobalt magnets and, more recently, Neodymium-Iron-Boron materials. FEL undulators employing these materials have, however, been limited to centimeter periods primarily due to the difficulty of handling tiny individual magnets which develop large physical force. Non-traditional undulator geometries that produce millimeter period fields suitable for the generation of far infrared radiation with compact low voltage accelerators are discussed. An analytical evaluation of the fields produced by these configurations is presented.

MATERIALS

The field reversal pattern of an FEL undulator (see Fig. 1) results in an inherently high reluctance structure and consequently, a large demagnetizing force at most points within the structure. Prior to the advent of Samarium-Cobalt materials with coercive force Hci > 10e4 Oe, permanent magnet undulators of, for example, Alnico 5 (Hci ~10e3 Oe) would have produced impractically feeble fields. More recently, Neodymium-Iron-Boron materials with residual fields as high as 12.5 KG [1] have increased the attainable peak field by ~25% over Samarium-Cobalt, while improved mechanical properties such as brittleness and tensile strength have eased design limitations. Mechanical strength problems in fact necessitated the sheathing of each individual magnet of the UCSB undulator with stainless steel (magnet dimmensions: 8.5 X 8.5 X 100 MM).

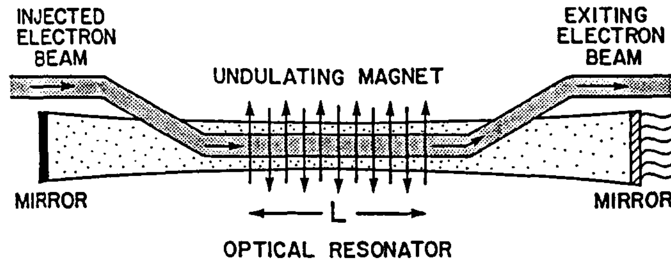

Fig. 1 Schematic representation of an FEL. A relativistic electron beam is transversely accelerated by a periodically reversing magnetic field. Electromagnetic energy emitted by the electrons is captured and stored between mirrors of a resonator.

MICRO-UNDULATORS

FELs generate light of wavelength $\lambda=\lambda_0/2\gamma^2$, where λ_0 = undulator period and γ, the relativistic mass ratio, is $qV/m_0c^2 + 1$. The present UCSB FEL generates light between 400μ and 110μ corresponding to energies between 3 and 6 MEV. Generation of submillimeter wavelengths with smaller electrosatic accelerators (E = 1 to 2 MEV) or generation of infrared wavelengths with higher voltage machines, requires undulator periods in the millimeter range rather than the centimeter range (3.6 CM) of the present UCSB machine.

Conventional undulators, such as the Halbach configuration used in the UCSB FEL, consist of individual magnets with successively rotated magnetic orientation. Recognition of the difficulty of handling individual magnets of the dimmensions required for a short period undulator motivated the development of alternate configurations that we refer to as "Micro-undulators"[2]. These structures consist of grooves ground in large blocks of material(see Fig. 2a and 2b). Periods as short as 1MM using blocks of approximately 5 X 5 CM appear practical. The field orientation of the blocks of Fig. 2a forces flux return paths to exist around the edges and ends, resulting in deleterious transverse quadrupole fields and axial end fields. This configuration is considered because blocks of this orientation are readily available. The configuration of Fig. 2b not only avoids the quadrupole fields but its end fields can be shaped to provide electron beam injection dipoles. "Cross-field" material of this type is presently available only in Samarium-Cobalt and with lower Br.

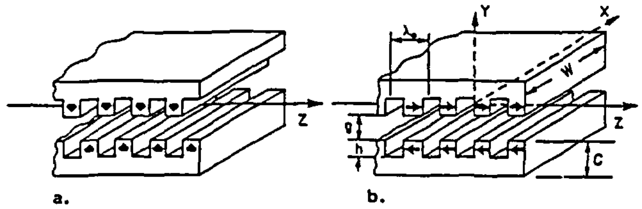

Fig. 2 Micro-undulator configurations

FIELD ANALYSIS

A full three dimmensional analysis of the Micro-undulator fields of Fig. 2a, based on the assumption of an ideal magnet i.e., uniform M with delta function discontinuities at each surface, yields

$$B_y = \frac{2\mu_0 M}{\pi} \sum_{n_{odd}} \frac{(-1)^{(n-1)/2}}{n} (1-e^{-2\pi nh/\lambda_0}) e^{-n\pi g/\lambda_0} \cosh\left(\frac{2\pi ny}{\lambda_0}\right) \sin\left(\frac{2\pi nz}{\lambda_0}\right) \left[1 - \frac{2\lambda_0}{\pi^2 g}\left(e^{-\pi\frac{(w+2x)^2}{2\lambda_0 g}} + e^{-\pi\frac{(w-2x)^2}{2\lambda_0 g}}\right)\right] \quad (1)$$

$$B_z = \frac{2\mu_0 M}{\pi} \sum_{n_{odd}} \frac{(-1)^{(n-1)/2}}{2} (1-e^{-2\pi nh/\lambda_0}) e^{-n\pi g/\lambda_0} \sinh\left(\frac{2\pi ny}{\lambda_0}\right) \cos\left(\frac{2\pi nz}{\lambda_0}\right) \left[1 - \frac{2\lambda_0}{\pi^2 g}\left(e^{-\pi\frac{(w+2x)^2}{2\lambda_0 g}} + e^{-\pi\frac{(w-2x)^2}{2\lambda_0 g}}\right)\right] \quad (2)$$

$$B_x = \frac{8\mu_0 M}{\pi^2 g^2} \sum_{n_{odd}} \frac{(-1)^{\frac{n-1}{2}}}{2} (1-e^{-\frac{2\pi nh}{\lambda_0}}) e^{-\frac{n\pi g}{\lambda_0}} \cosh\left(\frac{2\pi ny}{\lambda_0}\right) \sin\left(\frac{2\pi nz}{\lambda_0}\right) \left[(w-2x)e^{-\frac{\pi(w-2x)^2}{2\lambda_0 g}} - (w+2x)e^{-\frac{\pi(w+2x)^2}{2\lambda_0 g}}\right] \quad (3)$$

Fig.3 plots By as a function of y for several harmonics (eqn. 1). Odd harmonic components, though larger than those of the Halbach configuration, are still quite reasonable. For example a period of 4.5 MM and a gap of 3 MM results in a .5% third harmonic.

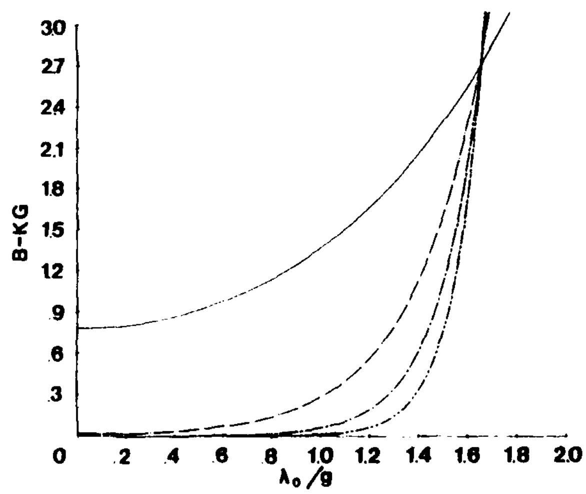

Fig. 3 Plot of By and its harmonic content as a function of y

CONCLUSION

The micro-undulator concept represents an application of modern magnetic materials that promises compact low voltage electrostatic accelerator FELs for the submillimeter region and infrared FELs with higher voltage electrostatic machines.

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